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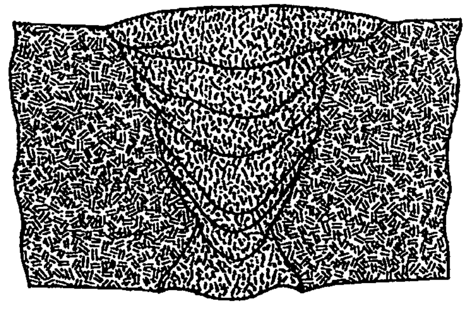
(54) Title: PROCESS FOR KEYHOLE WELDING

(57) Abstract

A process for welding metal workpieces using a gas tungsten arc welding operation, the metal workpieces having a front side from which welding is conducted and a rear side, wherein, during the welding, appropriate conditions are maintained to create an open keyhole such that efflux plasma is vented through the keyhole to the rear of the workpieces.



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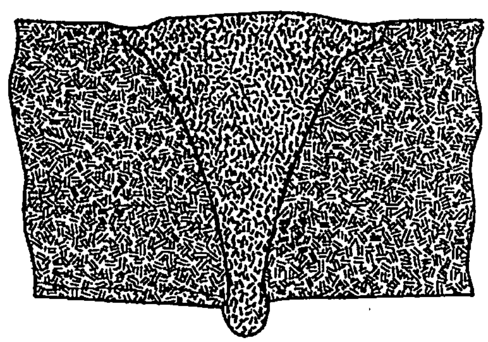

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PROCESS FOR KEYHOLE WELDING

Field of the Invention

The present invention relates to a process for keyhole welding, and in particular to a process for keyhole welding using gas-tungsten arc (GTA) welding principles.

Background of the Invention

Keyhole welding is a fusion process in which welding energy is deposited deep within a joint via a cavity, or keyhole, extending from the surface of the material being joined. The cavity must be formed as part of the welding process, and results from the combined action of highly localised energy and pressure.

The energy for welding may be delivered by a beam, as in laser and electron beam welding, or a current-carrying jet of plasma (also referred to as an arc), as in plasma arc welding and (as will be seen below) the process of the present invention. The keyhole forms as the material of the workpieces in the path of the beam or jet is melted and forced aside by the beam or jet. This displacement is due to an increase in pressure in the interaction region. For laser and electron beams the pressure is generated by the ablation of material from the walls of the keyhole, whereas for plasma jets a significant portion of the pressure results from the reaction of the jet against the walls of the keyhole. In either case, however, the keyhole radius will be limited because of the limited spatial extent and energy content of the beam or jet.

For the keyhole to be useful for welding, two additional conditions must apply. First, the keyhole must move with the beam or jet as the joint to be welded is traversed. Secondly, the liquid metal forming at the leading surface of the keyhole must flow around the keyhole walls to a trailing puddle where it will coalesce and subsequently solidify, thereby completing the weld with minimal displacement of material to either the front or rear side of the workpieces. These constraints

render acceptable keyhole dimensions and travel speeds dependent on various other parameters such as the thermo-physical properties of the workpieces, and the welding orientation with respect to gravity.

Unless the welding energy is sufficiently focussed, and achieves a relatively very high intensity, the keyhole cannot form, and the heat must be conducted from the surface through the liquid weld pool. This is the situation in the familiar forms of welding, such as oxy-acetylene welding and the various forms of electric arc welding and is referred to as the "melt-in mode".

The keyhole mode is normally associated with laser and electron beam welding, but can be achieved with plasma arc welding (PAW). The PAW process utilises a highly collimated arc formed by forcing the arc through an orifice in a copper alloy nozzle. The passage of the arc through the orifice is made possible by a rapidly flowing co-axial "plasma gas" which insulates the orifice walls, and allows the process to "keyhole". PAW keyholes differ from those generated with lasers or electron beams in that they must be "open". This means that the keyhole must extend all the way through the plate. If this does not occur, the plasma gases become trapped and give rise to excessive turbulence. The plasma escaping from the bottom of the keyhole is referred to as the "efflux" plasma.

In this respect, it should be appreciated that the term 'keyhole' is a general term and is applicable to both open keyholes and closed keyholes. For the cases of plasma arc welding and the process of the present invention (as will be apparent below) further qualification is required because only open keyholes can be usefully produced.

PAW is regarded as the only arc welding process typically operated in a keyhole mode. Indeed, it is frequently contrasted with GTA welding where the keyholing capability of PAW is seen as its primary advantage. The disadvantages of PAW in

comparison to GTA welding include greater capital costs, reduced parameter tolerance, greater complexity of the torch design, and higher maintenance.

GTA welding (known also as tungsten inert gas or TIG welding) is a precision welding method which has been used for many years to produce high quality joints in a wide variety of materials. It is a very clean process as no flux is used. It may be operated manually at lower welding currents to weld relatively thin materials, but requires careful V- or X-type edge preparation, by machining, for thicker sections. This in turn usually necessitates the addition of filler material and multiple passes to complete the joint, leading to significantly increased joint completion times.

As an alternative, the GTA welding process may be automated and operated at higher currents (ie >300 amps) to cause displacement of the weld pool, resulting in greater penetration, and permitting its application to joints between square-edged sections. This process variant is sometimes referred to as high current, buried arc, or immersed arc GTA welding. It is generally operated with direct current and with the electrode as the cathode because this polarity provides the greatest efficiency in energy delivery to the weldment.

However, because of the high arc pressures and turbulence generated in the weld pool when operating at such high current, severe defects such as porosity, cracking, humping and inclusions are commonly observed, as well as poor mechanical properties on occasions. To overcome problems of these types developments have aimed at reducing the arc pressure and stabilising the arc.

Reduction of arc pressure has been approached through a variety of measures including the use of electrodes with truncated or hollowed tips, application of high gas flow rates, the use of helium in the shielding gas, and the submerging of the electrode (the electrode tip is lowered into the weld pool cavity and is therefore below the level of the plate surface). Stabilisation of the arc has been improved

significantly by improved torch design, with particular attention given to stabilising the thermal gradients in the electrode through comprehensive cooling. The welding torch disclosed in applicant's international patent application PCT/AU95/00269 is an example of such improved torch design.

It is an aim of the present invention to provide a process for keyhole welding using GTA welding principles, thus avoiding the difficulties inherent in plasma arc keyhole welding.

Summary of the Invention

The present invention provides a process for welding metal workpieces using a gas tungsten arc welding operation, the metal workpieces having a front side from which welding is conducted and a rear side, wherein, during the welding, appropriate conditions are maintained to create an open keyhole such that efflux plasma is vented through the keyhole to the rear of the workpieces, and preferably such that non-turbulent weld pool motion is created.

The appropriate conditions may be such as the simultaneous application of high arc pressures and/or sufficient linear heat input such that the metal at the junction of the workpieces can be both melted and displaced to the extent that an open keyhole forms.

Furthermore, the appropriate conditions may alternatively or additionally include increasing the constriction of the arc (in terms explained below) to reduce the minimum required linear heat input, and/or to increase arc pressures independently of an increase in weld current.

Description of the Invention

In traditional arc welding of any sort (be it plasma arc welding or gas-tungsten arc welding) the arc exerts a force on the weld pool, and this force increases with the square of the magnitude of the welding current. This force is conveyed, at least in part, by the motion of plasma within the arc, resulting in a jet of plasma. The arc pressure associated with the arc force and its distribution is important in determining the resultant profile of the weld pool surface. The pressure of the arc is therefore dependent on both the distribution of the arc force and its magnitude (or by implication the welding current). It should also be appreciated that the arc pressure is dependent on the area over which the arc is distributed, and mechanisms which reduce this area can be said to constrict the arc. Constriction of the arc generally results in an increase in arc pressure without an attendant increase in current.

In relation to the process of the present invention, the keyhole GTA welding preferably requires the simultaneous application of high arc pressures and sufficient linear heat input such that the metal at the junction of the workpieces can be both melted and displaced to the extent that an open keyhole forms. The applicant has found that as the arc pressure increases, the pool motion becomes increasingly turbulent. However, on further increase of either the arc pressure or the linear heat input it is possible to reach an operating window in which the arc opens a cavity completely through the thickness of the workpieces (referred to as an open keyhole), and stable keyhole welding can be achieved. The onset of this regime corresponds to the venting of the plasma from the arc (referred to as the efflux plasma) through the bottom of the keyhole to the rear of the workpieces, and stable non-turbulent weld pool motion. In this respect, it is to be appreciated that, for the purposes of this specification, turbulent flow is to mean a flow pattern that changes significantly within a second or less.

Furthermore, this regime generally requires that the linear heat input be sufficient to melt enough metal for the keyhole to penetrate fully through the plate, but not so much as to create a molten region on the rear of the workpieces that is too large to be supported by surface tension forces (or other non-specified forces which may be applied). It is postulated that the process of this invention is conditional on the degree to which the arc is constricted, and in general, increasing the level of constriction is favourable to keyhole formation. In particular, increasing the degree of constriction reduces the minimum required linear heat input and renders the process of the present invention more tolerant to variations in the applied conditions.

In relation to linear heat input, it is difficult to specify the necessary linear heat input because an accurate prediction would need to take into account the differing thermo-physical properties of different metals and alloys, and also factors, such as welding speed, which affect the efficiency of the fusion process. However, it has been found that the minimum linear heat input required for keyholing with the process of the present invention can be estimated as follows:

$$Q = 12.5\, h\, (w+2)/1000$$

where Q is the linear heat input in kJ/mm if h is the thickness of the plate in millimetres, and w is the width, in millimetres, of the weld bead on the front side of the workpiece.

In relation to arc pressure, whilst the use of a high arc pressure is preferred for open keyhole formation, the required arc pressure is generally dependent on a variety of parameters that will vary from task to task. For instance, parameters such as the allowable linear heat input, and the thickness and type of material being welded, will determine the preferred arc pressure. Thus, in general terms, it should be appreciated that an arc pressure will be 'high' in the sense used in this specification if it subsequently creates an open keyhole such that the efflux plasma may be vented through the keyhole to the rear of the workpieces.

As with linear heat input, pressures within welding arcs are very difficult to measure, and consequently reference to them is of limited value. However, the mean arc pressure will be equal to the arc force divided by the area of the workpiece over which the arc is distributed. This area will be subsequently referred to as the arc impingement area. Furthermore, it is known that the arc force is proportional to the square of the magnitude of the arc current, 'I'. Therefore, if the parameter 'w' is such that w^2 is proportional to the arc impingement area, the parameter 'API' (an arc pressure indicator) may be defined as follows:

$$API = I^2/w^2$$

and thus may be used as an indicator of the mean arc pressure. In relation to API, the width of the resultant weld bead on the front surface of the workpieces will be used for the parameter w, and it will be appreciated that for this choice w^2 is only approximately proportional to the arc impingement area, and the constant of proportionality will vary for different materials, welding conditions, joint preparations and processes. Consequently the arc pressure indicator, API, defined above, is a practical, but approximate, indicator of the arc pressure, and it is possible that more useful parameters may be specified in the future. It is envisaged that APIs in the range of 900 to 8000 (amp^2/mm^2) will be suitable to provide the keyhole formation, preferably in the range of 1200 to 5000 (amp^2/mm^2) and more preferably in the range of 1400 to 4000 (amp^2/mm^2). This compares with traditional GTA welding APIs of 300 to 1000 (amp^2/mm^2) used for the melt-in mode welding processes.

To better illustrate examples of arc pressures and linear heat inputs that are suitably high, reference is now made to Tables 1a, 1b and 1c which show API's and linear heat inputs used in traditional GTA welding scenarios, compared to API's and linear heat inputs that are usable in the process of the present invention.

Scenario	Arc Pressure Indicator (amp^2/mm^2)	
	Keyhole mode	Melt-in mode
1	2090	522
2	1410	460
3	1850	710
4	3980	680

Table 1a **Comparison of arc pressure indicators for keyhole and melt-in mode GTA welding.**

Scenario	Number of Passes x Linear Heat Input (kJ/mm)			
	Keyhole mode		Melt-in mode	
	Predicted	*Actual*	*Predicted*	*Actual*
1	1 x 2.54	1 x 2.34	1 x 2.70	7 x 1.15
2	1 x 2.25	1 x 3.06	1 x 2.00	5 x 1.08
3	1 x 0.70	1 x 0.80	1 x 0.96	2 x 1.15
4	1 x 0.75	1 x 0.85	1 x 0.94	2 x 1.25

Table 1b **Comparisons between predicted linear heat inputs required for keyholing against actual linear heat inputs for various welding scenarios.**

Scenario & Welding	Welding Mode	Welding Parameters				
		Electrode	Shield.gas	Current (*amps*)	Weld speed (*mm/min*)	Bead width (*mm*)
#1: 12mm	Keyhole	6.4-Ce-45	Ar-10N	640	300	15
AISI304	Melt-in	3.2-Ce-60	Argon	320	200	16
#2: 10mm	Keyhole	6.4-Ce-45	Argon	600	200	16
3Cr12	Melt-in	3.2-Ce-60	Argon	300	200	14
#3: 5.1mm	Keyhole	4.8-Ce-60	Ar-3N	430	450	9
SAF2205	Melt-in	3.2-La-45	Argon	240	150	13
#4: 5.0mm	Keyhole	6.4-Ce-60	Argon	505	500	10
C-Mu Steel	Melt-in	3.2-Ce-60	Argon	260	150	13

Table 1c Conditions applying to the different scenarios of Table 1a.

Notes:

1. Electrode information is presented as 'Diameter in mm – Rare earth additive – Included angle of the tip'.
2. Shielding gas information is presented as 'Predominant gas – Percentage of second gas, second gas'.
3. All welds were made with automated equipment.

In preferred forms of the process of the present invention, additional steps may be taken to assist in the formation of keyholes. In relation to the tungsten electrodes used in the GTA welding torches, it is preferable to maintain the electrodes at a negative polarity with respect to the workpieces. This has been found to produce a more stable arc and less heating of the electrode than other polarities.

Further, it is preferred to use electrodes with enhanced electron emission characteristics in order to increase the current density at the electrode tip. It is also preferred to reduce the included angle of the electrode tip, for instance to about 45°, in order to increase the surface area of the electrode in contact with the

arc for a given arc cross section, and to reduce the electrical stick-out of the electrodes to about 5mm in order to improve the heat dissipation from the electrode tip.

Further still, it is believed that improving the heat transfer away from the electrode tip, for instance by improved cooling of the electrode, will also assist in the creation of keyholes by reducing the area of emission of the electrode, thereby increasing the current density within the arc.

The process of the present invention may further benefit by the careful selection of suitable shielding gases. For instance, it is preferred to use diatomic gases (such as hydrogen or nitrogen) in the shielding gas, and to avoid gases such as helium. Of course, it should be appreciated that the weld quality of some materials will deteriorate if nitrogen or hydrogen is added to the shielding gas.

In addition to the foregoing, it may be beneficial to stiffen the arc through high frequency oscillations of the welding current. Selection of appropriate levels for these parameters will again be case specific and will often be determined by virtue of constraints placed by other parameters. For example, for many materials the range of usable arc pressures may set a well defined upper limit for the travel speed, and this may particularly be the case for thick workpieces or highly conductive materials.

It should be noted that all of these preferred features result in an increase in the current density within the arc, and therefore can be appreciated as mechanisms for constricting the arc. It is evident, however, that the arc pressure will be strongly influenced by variations in the welding current, and this is the means by which the process of the present invention is preferably regulated during operation. Varying the travel speed and the arc voltage may further regulate the process, as these variables permit the linear heat input to be varied independently of arc pressure.

In addition to using necessary arc pressures and linear heat inputs, the successful formation of an open keyhole requires that the efflux plasma be adequately vented. Thus, the process of the present invention preferably avoids the use of backing plates or bars, the use of which is common practice with conventional and high current GTA welding, but which would impede the venting of the efflux plasma. Similarly, the use of any extended solid surface at the rear of the workpieces, such as a welding table in close proximity to the rear face of the weld, is preferably avoided.

The process of the present invention has been found to be relatively fast and capable of producing completed joints in a single pass. It is most suitable to use square butt joints, and the process can be used with or without the addition of filler material. The process is suitable for a wide range of materials, but is most easily applied to those with relatively low thermal conductivities. Suitable materials include carbon-manganese and stainless steels and titanium in thicknesses up to at least 12mm. In particular, the process of the present invention can be conducted using existing, unmodified high current GTA welding equipment (such as that described in PCT/AU95/00269), it can achieve relatively high welding speeds, joints may be completed in a single pass, it can complete joints with less heat input and distortion than conventional GTA welding or GMA welding, it operates with DC electrode negative polarity for greatest efficiency, and edge preparation is minimised (only square butt edges are required).

An example of welding parameters used to achieve an open keyhole weld in 12mm stainless steel in accordance with the process of the present invention is presented in Table 2. The parameters are contrasted with those of a conventional GTA welding procedure for the same material.

Parameter	Keyhole GTA Welding	Conventional GTA Welding
Material	12mm AISI 304	12mm AISI 304
Edge preparation	Closed square butt	V-prep with 60° included angle
Number of passes	1	7
Electrode	6.35mm ö ceriated tungsten	3.2 mm ö ceriated tungsten
Electrode tip	Conical with 45° included angle	Conical with 60° included angle
Shielding gas	90% argon with 10% nitrogen	100% argon
Filler addition	Yes	Yes
Arc voltage (volts)	17.0	11.5
Arc current (amps)	640	320
Travel speed (mm/min)	300	200
Heat input/pass (kJ/min)	2.18	1.10
Total heat input (kJ/min)	2.18	7 x 1.10
Welding time (per metre)	3 min 20 sec	35 min

Table 2 **Comparison between welding parameters for keyhole and conventional GTA welding. The conventional welding procedure was taken from ASM International, *ASM Handbook*, Vol 6, pp 195 – 199, 1993.**

The comparisons in Table 2 reveal certain benefits achieved by the keyhole GTA welding of the process of the present invention over the conventional GTA welding. In particular, the keyhole GTA welding process requires much less expensive edge preparation, is faster, involves less total heat input, and consequently less distortion, and uses less filler material and less shielding gas.

The difference between fusion zone profiles for a keyhole GTA weld and a conventional GTA weld is highlighted by the representations of macrographs presented in Figures 1a and 1b, Figure 1a representing a fusion zone profile in 12mm AISI304 for conventional GTA welding, and Figure 1b representing a fusion zone profile in 12mm AISI304 for the keyhole GTA welding of the present invention. From these representations it is apparent that the fusion zone for the keyhole GTA process is smaller than for the conventional process, and has been created with a single pass.

Finally, it will be understood that there may be other modifications or variations made to the process and features described above that are also within the scope of the present invention.

CLAIMS:

1. A process for welding metal workpieces using a gas tungsten arc welding operation, the metal workpieces having a front side from which welding is conducted and a rear side, wherein, during the welding, appropriate conditions are maintained to create an open keyhole such that efflux plasma is vented through the keyhole to the rear of the workpieces.

2. A process according to claim 1 wherein appropriate conditions are maintained such that, additionally, non-turbulent weld pool motion is created.

3. A process according to claim 1 or claim 2 wherein the appropriate conditions include the simultaneous application of high arc pressures and/or sufficient linear heat input, such that the metal at the junction of the workpieces can be both melted and displaced to the extent that an open keyhole forms.

4. A process according to claim 3 wherein the appropriate conditions additionally include increasing the constriction of the arc to reduce the minimum required linear heat input, and/or to increase arc pressures independently of an increase in weld current.

5. A process according to claim 1 or claim 2 wherein the appropriate conditions include increasing the constriction of the arc to reduce the minimum required linear heat input, and/or to increase arc pressures independently of an increase in weld current

6. A process according to any one of claims 3 to 5 wherein the minimum linear heat input required is estimated as follows:

$$Q = 12.5\ h\ (w+2)/1000$$

where Q is the linear heat input in kJ/mm if h is the thickness of the workpiece in millimetres, and w is the width, in millimetres, of the weld bead on the front side of the workpiece.

7. A process according to any one of claims 3 to 5 wherein a mean arc pressure is defined as

$$API = I^2/w^2$$

where API is an arc pressure indicator, w is the width, in millimetres, of the weld bead on the front side of the workpiece, and I is the arc current.

8. A process according to claim 7 wherein the API is in the range of 900 to 8000 amp^2/mm^2.

9. A process according to claim 7 wherein the API is in the range of 1200 to 5000 amp^2/mm^2.

10. A process according to claim 7 wherein the API is in the range of 1400 to 4000 amp^2/mm^2.

11. A process according to any one of claims 1 to 10, the process additionally including maintaining tungsten electrodes at a negative polarity with respect to the workpieces.

12. A process according to any one of claims 1 to 11, the process additionally including the use of tungsten electrodes with enhanced electron emission characteristics in order to increase the current density at the electrode tip.

13. A process according to any one of claims 1 to 12, the process additionally including using a reduced included angle of the electrode tip, to about 45°, in order to increase the surface area of the electrode in contact with the arc for a given arc

cross section, and reducing the electrical stick-out of the electrodes to about 5mm in order to improve the heat dissipation from the electrode tip.

14. A process according to any one of claims 1 to 13, the process additionally including the use of shielding gases comprising diatomic gases such as hydrogen or nitrogen.

15. A workpiece welded by a process in accordance with the process of any one of claims 1 to 14.

16. A process according to claim 1 substantially as herein described in relation to Table 2.

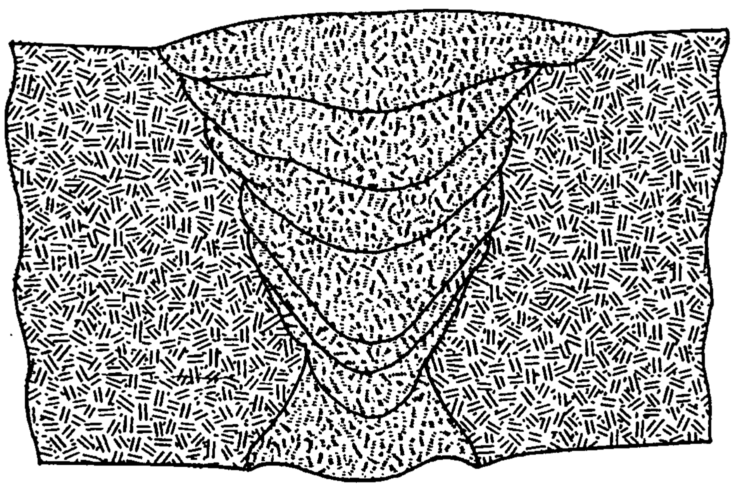

FIG 1a

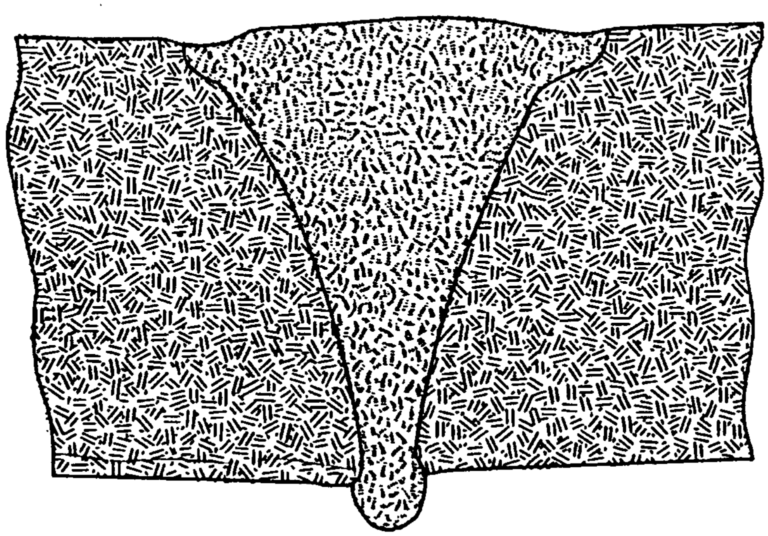

FIG 1b

INTERNATIONAL SEARCH REPORT	International application No. PCT/AU 98/00892

A. CLASSIFICATION OF SUBJECT MATTER

Int Cl[6]: B23K 9/167

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B23K 9/16, 9/167, 9/173

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU: IPC as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5347098 A (MURA KAMI et al) 13 September 1994 Column 4, line 66 - column 5, line 8	
P,A	US 5686002 A (FLOOD et al) 11 November 1997 Column 4, lines 56-67	
A	Patent Abstracts of Japan JP 06-320277 A (SHIMAKURA TEKKOSHO: KK) 24 November 1994 Abstract	

[X] Further documents are listed in the continuation of Box C

[X] See patent family annex

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 December 1998	18.12.98
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU 98/00892

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GB 1579601 A (CENTRAL ELECTRICITY GENERATING BOARD) 19 November 1980 Entire document	
A	US 4788409 A (Yamade et al) 29 November 1988 Entire document	
A	US 4195216 A (Beauchamp et al) 25 March 1980 Entire document	

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/AU 98/00892

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	5347098	CA	2073840	EP	523615	EP	664181
		JP	6339775	NO	922771		
US	5686002	AU	38289/97	WO	98/06529		
US	4788409	EP	256525	JP	63049367		
US	4195216	DE	2811643	FR	2383746	GB	1572847
		IT	1108707				

END OF ANNEX